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Analysis of an Emergency Diesel Generator Failure Incident in Nuclear Power Plants

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Abstract

A recent case of four EDG demand failures raised a concern for regulators and nuclear industry in general. Failures of EDGs can lead to station blackouts that would in turn cause a plant shut down. This study has been conducted to decide if the recent failure is a random/anticipated event of aging equipment that follows the historical statistics, and, or it is an extreme event that is unusual. The analysis of the study is centered on the correlation between historical EDG failures over the last few decades and the 2011 incidence. The object is to find the recurrence period and probability of high EDG demand failures. EDG demand failure data are accumulated for the period of 1980 – 2011 by using the published reports. Statistical analysis using the geometric and exponential distributions is applied to make predictions into the future. The study finds it is likely that the excessive EDG demand failure is not a 100-year event. It may come much sooner than believed; it is likely that the probability of excessive number of EDG failures per year is greater than 1%, and the average number of yearly EDG demand failure may remain to be 1 but with an unmistakable upward trend.

Introduction

The availability of electrical power is essential for the safe operation and accident recovery of nuclear power plants (NPP). Offsite power sources normally supply this essential power from the electrical grid to which the plant is connected. If the plant loses offsite power, emergency diesel generators (EDG) provide onsite electrical power. A total loss of power at an NPP as a result of complete failure of both offsite and onsite power sources, which rarely occurs, is referred to as a station blackout (SBO). Researches have examined EDG failures in the U.S. from 1997 to 2003 and calculated the average odds that an EDG would fail to work at some point during an eight-hour run were slightly greater than 2 or 3 percent [1]. In addition, it was calculated that an average of one EDG has failed when needed each year. However, a recent report of multiple EDG failures in 2011 in several nuclear power plants raised a concern both for regulators and of nuclear industry maintenance practices [2]. Such failures would lead to station blackouts that would in turn cause a plant shut down. The causes of the recent excessive number of EDG failures are still being under investigation by authorized bodies.

In regards to this excessive number of demand failures of EDG in 2011, an interesting question has been raised: when will be the next year with multiple EDG failures, and what is the probability of having such multiple EDG failures? In other words, we want to estimate the recurrence period (or return period) of excessive EDG demand failures, and thus the probability of having such an excessive event. To answer the question, we applied the basic extreme event analysis approach with simple geometric distribution function, to start with, and later an exponential distribution function. However, there is a fundamental problem in analyzing this EDG failure event since the event was the first and only event of having more than 2 EDG failures in a year. In other words, even though we may use geometric and exponential distribution approaches, this first event alone cannot provide appropriate return period of the next such high EDG failure year.

To overcome this fundamental problem, we took the 2011 event as if it was the mean, a value contained in the 68 % of the population, or a value contained in the 95% of the population of an unknown return period population of such high EDG failure years. Using this approach, we could see at least if prediction of next occurrence of excessive number of EDG failure is possible under the three different assumed treatments of the 2011 incident.

The paper is organized as follows. It first discusses the types of EDG failures relevant to the analysis and the sources of yearly EDG demand failure data accumulated for the analysis. Then, Chapter 3 analyzes the EDG failure data using the exponential probability distribution to predict the recurrence and probability of high EDG demand failure event. Chapter 4 concludes the paper.

EDG Demand Failure Data

As stated above, four emergency diesel generators that power emergency systems at the U.S. nuclear plants have failed when needed in 2011, which itself is an unusual cluster of event with excessive number EDG failures. A complete failure of timely operations of EDGs when needed, "EDG demand failure," may result in a SBO or complete loss of onsite and offsite power. EDG failures have been divided into specific types to better establish the proper labeling of these failures. The most common failures included in the "EDG demand failure" are: Failure to Start (FTS), Failure to Load and Run (FTLR), and Failure to Run >1 Hour (FTR1H). FTS is defined as "any failure that prevents from achieving a specified frequency (or speed) and voltage within certified limit", and FTLR as "a failure when EDG generator starts but does not pick up the load and run successfully" [3]. Any other failures reported during the periodic surveillance tests and false starts do not belong to the demand failure and are not considered in the paper.

The data for the analysis of the EDG demand failure are naturally depended first on NRC reports that have been documented regarding all possible types of EDG failures that have happened in the past. Unfortunately there are not any documented data that covered the entirety of that time. However, a report of NRC contained 1997-2003 periods of EDG failures [4] and this is the one source of our EDG demand failure data. Table 1 lists the yearly EDG demand failures from the report of the 3 types described above.

Table 1. Year EDG Demand Failure in the period of 1993-2003

Year	#	Year	#	Year	#
1993	0	1997	2	2001	0
1994	0	1998	0	2002	0
1995	1	1999	2	2003	0
1996	1	2000	2		

The second source of our data on EDG failure is the Licensee Event Report (LER), which is publicly available. LER is an event notification report that provides in depth details about a particular mishap, failure, or maintenance practice that has happened. It particularly lists each component that has failed, the type of failure that occurred and whether or not it has been repaired, if so, to what extent. LER reports first came about in January of 1980, extending back 32 years. Our LER search for the years 1980-1992 and 2004-2012 results in the following two tables, Table 2 and Table 3, of the yearly EDG demand failures:

Table 2. Year EDG Demand Failure in the period of 1980-1992

Year	#	Year	#	Year	#
1980	0	1985	0	1990	0
1981	0	1986	0	1991	0
1982	0	1987	0	1992	0
1983	0	1988	1		
1984	0	1989	0		

Table 3. Year EDG Demand Failure in the period of 2003-2011

Year	#	Year	#	Year	#
2003	0	2006	2	2009	0
2004	0	2007	0	2010	0
2005	2	2008	0	2011	4

Combining the 2 data sources, we make have the yearly EDG demand failure data for the 1980 – 2011 periods, as plotted in Fig.1.

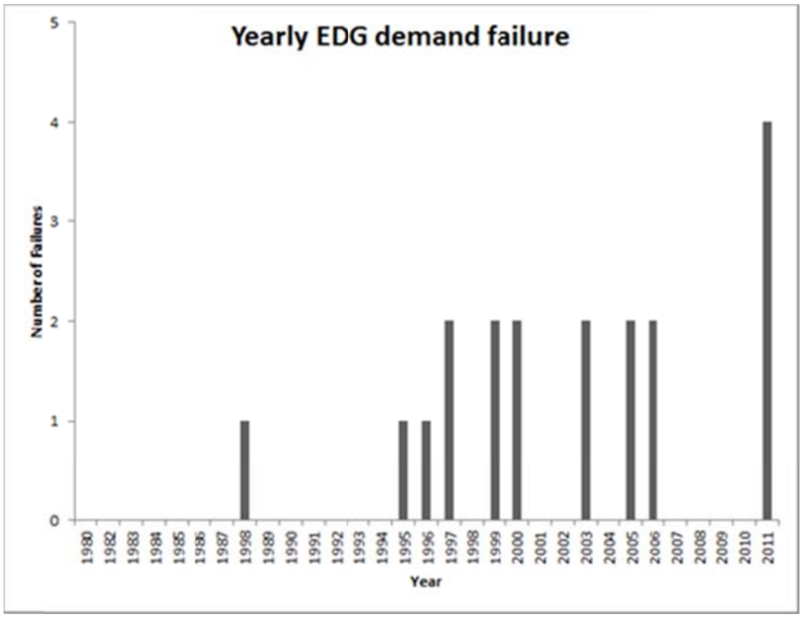

Fig.1. Yearly EDG demand failure in the period of 1980 – 2011.

As can be seen in Fig.1, the first EDG demand failure was reported in 1988. Therefore, there can be two views in determining the year 2011 (of excessive number of EDG failures) as the 23rd year (counted from the first EDG failure year 1988) and as the 31st year (counted from 1980 when EDG failure reporting started). In the analysis detailed in the next chapter, we apply the two views of N=23 and N=31 as the first occurrence year.

EDG Failure Analysis

The EDG failure analysis can be viewed as a simple statistical approach for the probability and the next year the similar incidence would occur. In doing so, a geometric distribution is first applied. We start our analysis with p as the probability of having an excessive event in a year, with q as $1 – p$. Then a density function of the geometric distribution is expressed by $f(\mathrm{k}) = p \cdot q^{(\mathrm{k}-1)}$, which is the probability of having an excessive event for the first time in k-th year. Then, the mean return period T of the excessive event is estimated as $1/p$, and the cumulative distribution function is obtained as $F(\mathrm{k}) = 1 - q^{\mathrm{k}}$, which indicates the probability that the excessive event occurs at the k-th year or before. This cumulative distribution function now can be approximated to an exponential function by the process explained here.

From $p = 1/T$ and $q = 1 – p$, with T a large number, which is a valid assumption, then
$F(\mathrm{k}) = 1 - q^{\mathrm{k}} = 1 – (1 – 1/T)^{\mathrm{k}} = 1 – \{ (1 – 1/T)^{T}\}^{\mathrm{k}/T} = 1 - \exp(-\mathrm{k}/T)$.

It tells us that once T is known, p is estimated, and $F(\mathrm{k})$ can be resulted, which will give us the probability of the occurrence of high EDG failures within next k years [5]. It is reminded however that the exponential equation of $F(\mathrm{k})$ is expressed by the mean return period T. In other words, the exponential distribution can be applied only when we have multiple excessive events and know the mean of the recurrence (return) period. Apparently, we have a problem because the excessive event of four EDG demand failures occurred only once and for the first time in 2011. In meeting the problem, we devised an approach. The approach is to use the N=23 or N=31 as if it is the mean, or lies within a boundary of an unknown return period population, then to draw $F(\mathrm{k})$ for each of the assumptions. The case of N as the mean return period is most unlikely, but the other two cases of N as a number in a range of return periods with 68% and 95% probability would be likely and most likely, respectively.

Under the most unlikely situation that the first observed year N is somehow the mean of the return period of the excessive event, then the probability of the excessive event $p = 1/\mathrm{N}$, and $q = 1 – p = (\mathrm{N}-1)/\mathrm{N}$, thus the probability of having the next excessive event at or before the k-th year is obtained as $F(\mathrm{k}) = 1 – \{(\mathrm{N}-1)/\mathrm{N}\}^{\mathrm{k}}$. In other words, in the unlikely case, the probability of more than 3 EDG demand failures per year is 1/N, and the mean recurrence period is N years. For N=23, the probability of having more than 3 EDG demand failures per year is 0.0435, and the return period is 23 years. For N=31 case, the corresponding values are 0.0323 and 31 years.

Now we consider more probable assumptions with emphasis on the simple expression for the probability that the excessive event will occur for the first time after T/r and before $T\cdot r$ years, where r is a unit of T [6]. Then, the (desired) probability of the year k being in the range of $T/r < k < T\cdot r$ can be approximated with only r:
$P(T/r < k < T\cdot r) = F(T\cdot r) - F(T/r) = \exp(-1/r) - \exp(-r)$.

If the desired probability is 0.5, for example, r is 2.2, then the range of k is $0.455T < k < 2.2T$. In other words, the first excessive year observed k lies in $[0.455T, 2.2T]$ and lies within the 50% of the population of return periods whose mean is T. Further, by similar calculation, we get the range of the observed year k accounted for 68% and 95% the return periods, respectively, which for normal distribution, corresponds to the one-sigma deviation and two-sigma deviations. The ranges of the observed year k are, then:
Accounted for 68%: $r = 3.129$, $0.3196T < k < 3.129T$.
Accounted for 95%: $r = 21.485$, $0.04657T < k < 21.485T$.

Under the likely situation that the first observed year of the excessive number of EDG failures is in the range of $0.3196T < k < 3.129T$ for the mean T of unknown return period population, the N can be taken as the two extreme values of the range, $N=0.3196T$ and $N=3.129T$. From these two relationships, we can get the likely range of the return period, [N/3.129, N/0.3196], which will in turn gives the likely rage of probability of more than 3 EDG failures in a year as [0.3196/N, 3.129/N]. Therefore, for N=23, the probability of having more than 3 EDG demand failures per year is [0.0139, 0.136], and the return period is [7, 72] years. For N=31 case, the corresponding values are [0.0103, 0.1009] and [10, 97] years.

Under the most likely situation that the first observed year of the excessive number of EDG failures is in the range of $0.04657T < k < 21.485T$ for the mean T of unknown return period population, the N can be taken similarly as the two extreme values of the range, $N=0.04657T$ and $N=21.485T$. In the similar manner, we get the most likely range of the return period, [N/21.485, N/0.04657], which will in turn gives the most likely rage of probability of more than 3 EDG failures in a year as [0.04657/N, 21.485/N]. Hence, in N=23, the probability of having more than 3 EDG demand failures per year is [0.002, 0.93], and the return period is [1, 494] years. Under N=31 case, the corresponding values are [0.0015, 0.69] and [1, 666] years.

In summarizing the analysis results, we meet too wide ranges of probability and return period to use in predicting the probability and the next occurrence year of the excessive EDG demand failures. Nonetheless, we have the following findings:

1. Until we have next excessive demand failure year, prediction of the probability and the next occurrence year of such failures, with an acceptable confidence level, is very difficult.
2. It is likely that the probability of excessive EDG demand failures per year is greater than 1%, and that the failure will not be a 100-yeaer event, though; it may come much sooner than believed.
3. The number of yearly EDG demand failure may remain to be 1, but as Fig.1 shows, the trend of more than 1 failure is unmistakable.

Conclusions

The unusually high number of EDG demand failure in 2011 stimulated interesting research questions. This paper attempted to analyze the incident in the hope that we might provide some basic study on the prediction of the next occurrence year of such high EDG failures and its probability. We accumulated EDG demand failure data in the period of 1980 – 2011 using published NRC reports and the LERs, and then applied geometric and exponential distributions. We found that (1) it was likely that the excessive EDG demand failure was not a 100-yeaer event and it might come much sooner than believed, and that the probability of excessive number EDG demand failures per year was greater than 1%; and (2) the average number of yearly EDG demand failure might remain to be 1 but the upward trend for more was unmistakable.

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